Scheduling of Real-Time Embedded Systems under Reliability and Power Constraints

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***Abstract*—In this paper, we present a new tri-criteria scheduling heuristic for scheduling data-flow graphs of operations onto parallel heterogeneous architectures according to three criteria: first the minimization of the schedule length crucial for real-time systems, second the maximization of the system reliability crucial for dependable systems, and third minimizing energy consumption crucial for autonomous systems. The proposed algorithm is a list scheduling heuristics, It uses the active replication of operations to improve the reliability and the dynamic voltage scaling to minimize the energy consumption.**

Keywords: Distributed real-time systems, safety-critical systems, reliability, multi-criteria scheduling, heterogeneous systems, active software replication.

I. Introduction

Distributed systems are being increasingly used in critical real-time applications, such as avionics, air traffic control, autopilot systems, and nuclear plant control, in which the consequences of missing a tasks deadline may cause catastrophic loss of money, time, or even human life. This is why such systems require a high reliability. Here, reliability is defined as the probability that none of the system components will fail while processing.

We present a scheduling heuristics that, from a given software application graph and a given multiprocessor architecture, produces a static multiprocessor schedule that optimizes three criteria: its *length* (crucial for real-time systems), its *reliability* (crucial for dependable systems), and its *power consumption* (crucial for autonomous systems).

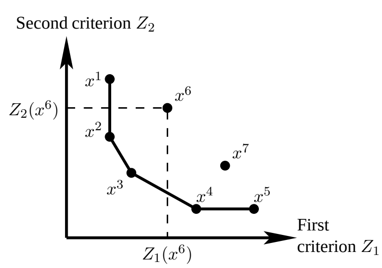

Fig. 1. Pareto optima and Pareto curve for a bicriteria minimization problem.

Let us address the issues raised by multicriteria optimization. Figure 1(a) illustrates the particular case of two criteria to be minimized. Each point x^1 to x^7 represents a solution, that is, a different tradeoff between the Z_1 and Z_2 criteria: the points x^1, x^2, x^3, x^4, and x^5 are *Pareto optima* [13]; the points x^1 and x^5 are *weak optima* while the points x^2, x^3, and x^4 are *strong optima*. The set of all Pareto optima is called the *Pareto curve*.

It is fundamental to understand that no single solution among the points x^2, x^3, and x^4 (the strong Pareto optima) can be said, a priori, to be the best one. Indeed, those three solutions are *non-comparable*, so choosing among them can only be done by the user, depending on the precise requirements of his/her application.

The main contribution of this paper is TSH, the first tricriteria scheduling heuristics able to produce, starting from an application algorithm graph and an architecture model, a set of Pareto solutions in the space (length, reliability, power), and taking into account the relationship between the reliability and the voltage level. In addition, the power consumption of both operations and data-dependencies are considered in this paper and the soundness of TSH is demonstrated.

II. Related work

Many solutions exist in the literature to optimize the schedule length and the energy consumption (e.g., [10]), or to optimize the schedule length and the reliability (e.g., [5]), but very few tackle the problem of optimizing the three criteria (length,reliability,energy). The closest to our work are [11], [14].

Zhu et al. have studied the impact of the supply voltage on the failure rate [14], in a passive redundancy framework (primary backup approach). They use DFS and DVS to lower the energy consumption and they study the tradeoff between the energy consumption and the performability (defined as the probability of finishing the application correctly within its deadline in the presence of faults).However, their input problem is not a multiprocessor scheduling one since they study the system as a single monolithic operation executed on a single processor.

Pop et al. have addressed the tricriteria optimization problem (length,reliability,energy) on an heterogeneous architecture with a reliable bus [11]. Both the length and the reliability are taken as a constraint, respectively with a given upper and lower bound. However, it is assumed that the user will specify the number of processor failures to be tolerated (with re-execution or passive replication) in order to satisfy the desired reliability constraint.

III. Models

A. Application algorithm graph

Most embedded real-time systems are reactive, and therefore consist of some algorithm executed periodically, triggered by a periodic execution clock. Our model is therefore that of an application algorithm graph $\mathcal{A}lg$ which is repeated infinitely. $\mathcal{A}lg$ is an *acyclic oriented graph* $(\mathcal{X}, \mathcal{D})$. Its nodes (the set $\mathcal{X}$) are software blocks called *operations*. Each arc of $\mathcal{A}lg$ (the set $\mathcal{D}$) is a *data-dependency* between two operations. If $X \triangleright Y$ is a data-dependency, then X is a *predecessor* operation of operation Y, while Y is a *successor* operation of X. Operation X is also called the *source* of the data-dependency $X \triangleright Y$,

Ismail Assayad is with ENSEM (RTSE team). Partially funded by DEV-RS 2011/14 CNRST project.

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